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Review

Interstellar Scintillation and Scattering of Micro-arc-second AGN

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Abstract: The discovery of the first quasar 3C 273 led directly to the discovery of their variability at optical and radio wavelengths. We review the radio variability observations, in particular the variability found at frequencies below 1 GHz, as well as those exhibiting intra-day variability (IDV) at cm wavelengths. Observations have shown that IDV arises principally from scintillation caused by scattering in the ionized interstellar medium of our Galaxy. The sensitivity of interstellar scintillation towards source angular sizes has provided a powerful tool for studying the most compact components of radio-loud AGN at microarcsecond and milliarcsecond scale resolution.

Keywords: quasars; variability; interstellar scattering

1. 1965–1980s: Low Frequency Variability

Following the identification of the first quasar 3C 273 [1,2], quasar variability was observed at optical wavelengths [3], and then at the radio wavelengths of 3.75 cm [4] and 32.5 cm [5]. At 3.75 cm, the variability was interpreted as intrinsic to the sources, as the observations displayed a timescale of a year or more. However, at lower frequencies the observed variability of CTA102 did not fit this pattern. Sholomitskii's published 1964–65 Soviet telescope data is shown in Figure 1, for which he claimed detection of variability at 32.5 cm wavelength on a time-scale of months or less.

Compared with the shorter wavelength observations, the implied brightness temperature at 32.5 cm wavelength is in excess of 10^{16} K and was unacceptably high. Sholomitskii's observations and their interpretation were not taken seriously in the West, given the implied extreme brightness temperature and the lack of knowledge of Sholomitskii's telescope and its performance. A 1999 photo of Sholomitskii's antenna is also shown in Figure 1.

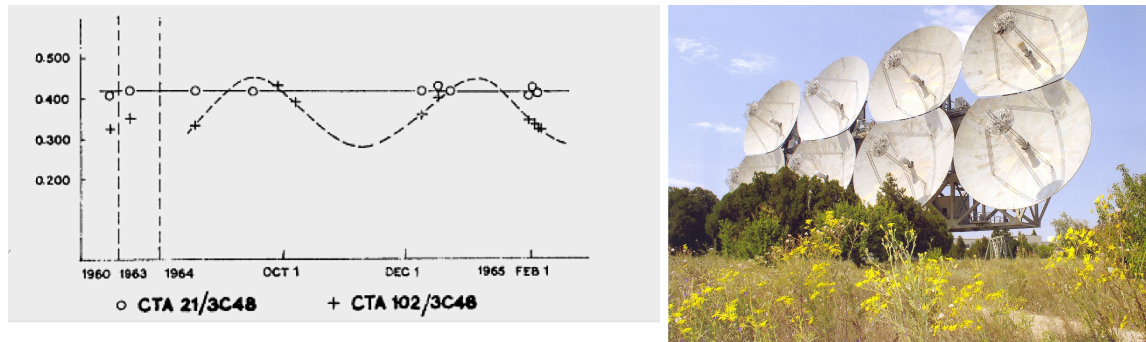


Figure 1. (Left) Sholomitskii's published 32.5 cm variability data through February 1965 [5], reproduced with permission; (Right) A 1999 photo of ADU 1000, Sholomitskii's original antenna (courtesy of L. Gurvits).

Soon afterwards, Hunstead [6] published a 5 year 408 MHz Mills Cross study of the observed variability of four sources, including CTA102, confirming the variability seen by Sholomitskii. Hunstead also observed 408 MHz variability in the quasar 3C 454.3 and the radio galaxies PKS 1504-167 and PKS 1524-13. He suggested several possible explanations, one of which was that the observed variability could be caused by slow scintillation in the inter-stellar or inter-galactic medium.

Following Hunstead's discovery, several studies of low frequency variability were undertaken on a variety of telescopes. It soon became clear that low frequency variability was relatively common (cf. [7,8]). At 408 MHz it was found that 25% of the compact sources studied showed variability, as did 51% of the flat-spectrum sources [7]. Soon afterwards, Rickett et al. proposed "that other slow variations in source intensity, particularly those of 'low frequency variables' may also be caused by the interstellar medium" [9]. The extra-galactic sources were scintillating just like pulsars.

2. 1980s–2002: Intra-Day Variability at Centimetre Wavelengths and Its Origin

In 1979, Heeschen commenced a 9 cm wavelength study with the NRAO 300' telescope of 226 steep- and flat-spectrum sources, searching for changes on timescales of 2–20 days [10]. He found no significant variability amongst the steep-spectrum sources, but the flat-spectrum sources did vary with average amplitudes of $\sim 1.5\%$. He suggested that such "flickering" may be caused by scintillation in the interstellar medium, or it may be intrinsic. He reported no correlation with Galactic latitude, a point against interstellar scintillation as the cause [11]. A more detailed analysis was undertaken of the same data concluding that the flickering did in fact exhibit latitude dependence consistent with refractive interstellar scintillation [12].

Heeschen followed this with observations of 15 flat-spectrum high declination sources at 2.7 GHz using the Effelsberg 100 m telescope, yielding some unexpected and spectacular results. They observed more of the flickering seen earlier, and in addition found some sources exhibiting up to 10% variability on a timescale of 1–2 days. Two examples, 0716+71 and 0917+62, are shown in Figure 2. This was the beginning of the study of radio intra-day variability, IDV, as we know it. They discussed three possible mechanisms responsible for this IDV and concluded that, of the three, refractive scintillation in the interstellar medium was the most likely [13].

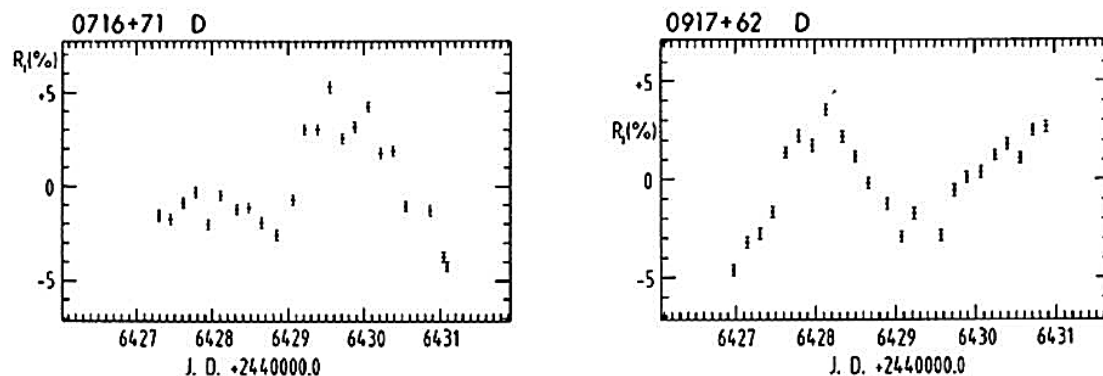


Figure 2. 2.7 GHz observations of 0716+71 and 0917+62 with the Effelsberg 100 m telescope, from [13] DOI:10.1086/114583. ©AAS. Reproduced with permission from AAS.

A significant change occurred soon afterwards as a result of a four-week simultaneous radio-optical monitoring campaign, including 0716+71, at the VLA, Effelsberg and the Calar Alto 2.2 m optical telescope [14]. Based on the VLA data at 5 GHz, they reported a close correlation of radio and optical IDV over a three day period, and noted that such a correlation implied that the radio variations could not be explained by refractive scintillation. These data were further examined and a strong correlation reported between the variations in the radio spectral index of 0716+71 between 5 and 8 GHz, and the observed optical variations [14], as shown in Figure 3.

Wagner and Witzel argued that, over these three days, the observed variations seen in the radio spectral index of 0716+71 and the observed optical variations, indicated a close correlation over five decades in wavelength, powerful evidence that radio IDV was intrinsic to the source [15]. Under these conditions, the radio brightness temperatures exceed 10^{17} K, implying relativistic beaming with very high Doppler factors.

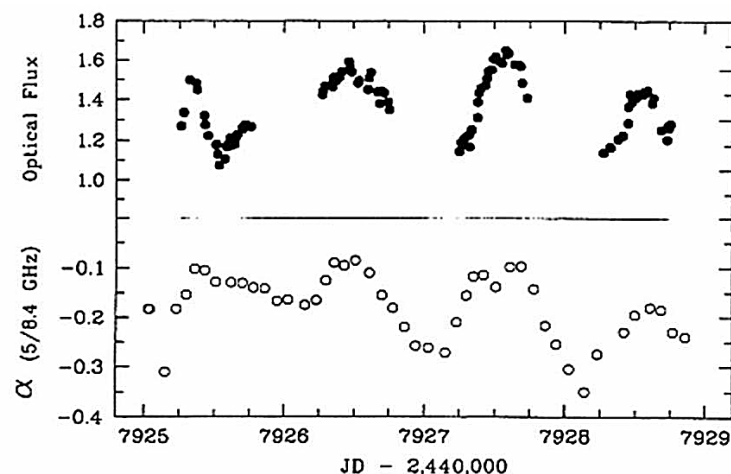


Figure 3. Observed correlations of the radio spectral index variability with the optical flux at 650 nm seen in 0716+714 [15]. Reproduced with permission from Annual Review of Astronomy and Astrophysics.

The discovery of the rapid intra-hour radio variable PKS 0405-385 caused a major change in interpretation. PKS 0405-385 exhibited very rapid IDV at 5 and 8 GHz on timescales of an hour or less; the discovery observations are shown in Figure 4. If this rapid variability was intrinsic, the implied brightness temperature was 10^{21} K. The variability-derived brightness temperature of a component boosted by Doppler factor D is enhanced by a factor D^3 [16], suggesting a Doppler factor $D > 1000$

would be required to reconcile the inferred brightness temperature with the inverse Compton limit of $\sim 10^{12}$ K in the rest frame of the source. However, the variation of variability amplitude and timescale with frequency was well described by refractive interstellar scintillation, ISS [17].

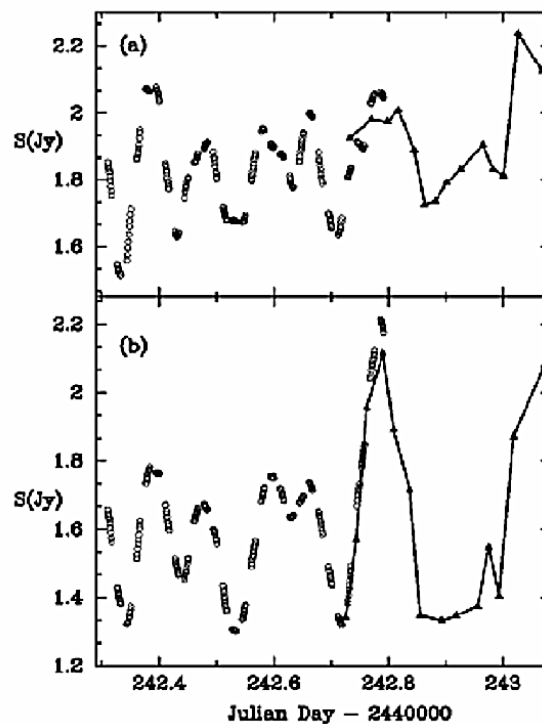


Figure 4. The combined ATCA and HARTRAO light curves for PKS0405-385 on 8 June 1996 at (a) 8.6/8.4 GHz and (b) 4.8/5.0 GHz, from [17] DOI:10.1086/311001. ©AAS. Reproduced with permission from AAS.

Based on their 15 GHz observations of the gravitationally lensed source B0218+357, Biggs et al. (2001) [18] claimed that the variability on a timescale of a few days seen in the two flat-spectrum lensed components could not be due to ISS or microlensing, and must therefore be intrinsic with a brightness temperature in the range of 10^{14} – 10^{15} K. In this case a Doppler factor $D \leq 10$ was required to reconcile the inferred brightness temperature with the inverse Compton limit, which is comparable to Doppler factors derived from very long baseline (VLBI) observations of the general blazar population. A more recent analysis of the Biggs et al. data for B0218+357 [19], showed that the observed flux density variations were well modelled by Gaussian components with peak flux densities of ~ 0.01 – 0.07 Jy, and timescales up to 10–20 days. The model was of separate plasmon injections in regions very close to the base of the collimation region in the jet. The difference between the behaviour at 15 and 8.4 GHz was well modelled by opacity effects close to the base of the jet. The longer timescales and much reduced flux density components reduce the implied brightness temperatures by factors of 100 or more, to 10^{12} – 10^{13} K.

Meanwhile, the rapid and large-amplitude variability of PKS 0405-385 provided an opportunity to reliably determine if these variations were intrinsic or were caused by ISS. Simultaneous precision flux density measurements at 4.86 GHz made with the VLA and the ATCA showed a two minute time difference between the arrival times of the variability patterns at the two telescopes, demonstrating that interstellar scintillation is the origin of the rapid IDV of PKS 0405-385, while at the same time ruling out an intrinsic origin [20].

Soon after the discovery of PKS 0405-385, two more intra-hour variables were discovered, J1819+3845 [21], and PKS 1257-326 [22]. These three sources have proven valuable in investigating

the ISS phenomenon, as many IDV cycles can be observed in a very short time. Pattern time delay measurements followed for J1819+3845 between the VLA and Westerbork [23] and for PKS 1257-326 between the ATCA and the VLA [24]. Figure 5 shows the measured pattern time delay between the ATCA and the VLA for PKS 1257-326; pattern delay differences of up to 8 min were observed [24].

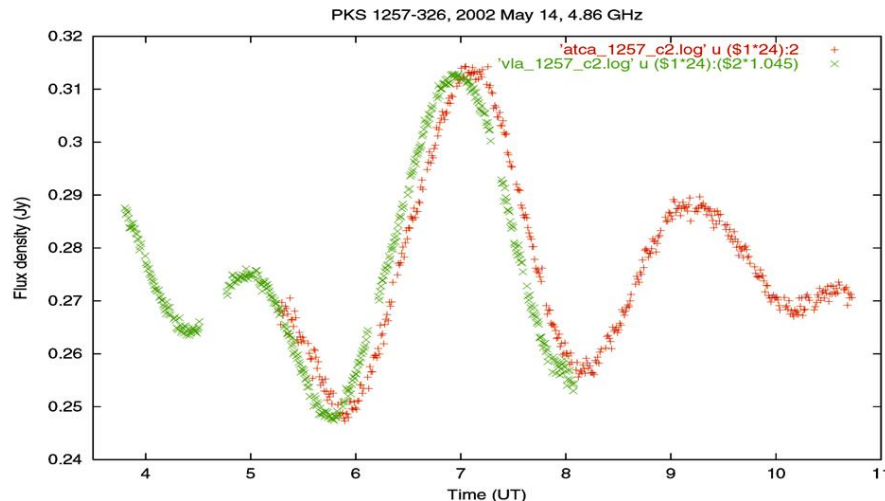


Figure 5. The time delay at 4.86 GHz between the ATCA and the VLA 14 May 2002 [25]. Reproduced with permission.

The role of ISS became even clearer with the discovery of an annual cycle in the variability pattern of J1819+3845; the annual motion of the Earth against the motion of the ISM shows up as a slowing down then speeding up of the variability pattern [26]. This phenomenon is also clearly present in the monitoring of PKS 1257-326 [22]. Moreover, it was also found to be present in the accumulated published variability data between 1985 and 1999 of the far northern IDV source 0917+624 [27,28]. The combination of the time delay measurements and the presence of an increasing number of IDV sources exhibiting an annual cycle was powerful evidence that refractive ISS was the dominant mechanism responsible for IDV at cm wavelengths.

The rapid variations in these three sources came about as they are viewed through very nearby plasma screens, and not due to any changes in the sources themselves. Careful Westerbork observations of J1819+3845 over the course of a year yielded a clear annual cycle, a nearby screen distance of no more than ~ 20 pc, and also a brightness temperature of $\sim 10^{13}$ K [26]. The other two rapid variables, PKS 0405-385 and PKS 1257-326, also have nearby scattering screens and similar brightness temperatures [29,30]. The screen velocities for these two sources also differ from the local standard of rest. A similar situation was found for the southern annual cycle scintillator PKS 1519-273 [31], and it was noted that the sight lines to PKS 1519-273, PKS 1257-326 and J1819+3845 pass through the edges of nearby partially ionized warm interstellar clouds where two or more clouds may interact [32].

3. 2002–Present: Statistical Studies and the Role of Interstellar Scattering

The MASIV (Micro-Arcsecond Scintillation Induced Variability) VLA Survey at 4.9 GHz set out to determine the fraction of flat-spectrum radio sources that exhibit ISS [33]. This year-long survey observed 500 AGN over each of four epochs of 3 or 4 days in 2002 and 2003. Each source was observed for 1 min every ~ 2 h when above 15° elevation. The sources were divided on the basis of their 5 GHz flux density into a strong, ≥ 1 Jy, and a weak, ≥ 0.1 Jy sample. A program of optical spectroscopy is also underway in order to provide the necessary reliable optical identifications and redshifts for as many of the MASIV sources as possible ([34] and references therein).

MASIV found that interstellar scintillation was a common phenomenon amongst flat-spectrum radio sources at cm wavelengths, with 56% exhibiting variations of 2% to 10% on timescales over

2 days [35], significantly more than had been found previously. The amplitude and timescale of the variations varies both with co-ordinates in the Galaxy and also with the source properties themselves. These findings amply confirm that the observed IDV is dominated by ISS, which depends on both the strength of the scattering material and the distance to the scattering region, and also on the fraction of the flux density that resides in the most compact component and its effective angular diameter.

Not unexpectedly, a significant dependence on Galactic latitude and also on the line-of-sight H-Alpha intensity, from the Wisconsin H-Alpha Mapper, WHAM, survey [36], was also apparent. Interestingly, there is a significant difference between northern and southern latitude sources. Overall, the observed timescales show that there are more sources with faster variations at high latitudes, and more sources with slow variations, interpreted as stronger refractive scattering, at low latitudes in both hemispheres. This clearly demonstrates that ISS is the dominant cause of such IDV for the compact radio source population as a whole [35]. The correlation between the strength of interstellar scattering and line-of-sight Galactic H-Alpha intensity was recently confirmed by a study of the angular sizes of an all-sky sample of more than 3000 sources at multiple frequencies measured using archival VLBI data [37].

The scintillation properties are also dependent on the source properties themselves. The weak and strong source samples differed significantly in that a larger fraction of the weaker sources were found to scintillate. They also exhibited larger fractional amplitudes of variability than the stronger sources. This is to be expected if the compact emission is limited by synchrotron self-absorption or inverse Compton losses to a maximum brightness temperature. In that case, the expected angular diameter increases as the square root of the mean flux density, which will then quench the ISS of the stronger sources. A simple model of the source and the ISM was investigated, with a typical screen distance of 500 pc and screen velocity of 50 km s⁻¹, and scintillating component of ~0.1 Jy, which leads to maximum brightness temperatures in the range 10¹² to 10¹⁴ K [35].

Rickett et al. [38] completed their analysis of the 146 sources in the 2 and 8 GHz Green Bank Interferometer variability survey. The sources were chosen on the basis of their known variability and/or compact VLBI structure. They found that the scintillation amplitude was stronger at 2 GHz than at 8 GHz, where 121 sources, 83%, were found to show ISS at 2 GHz. They modelled their observations using the NE2001 Galactic electron model assuming that the sources were brightness temperature limited, and had on average 50% of the flux density in a component with maximum brightness temperatures 10¹¹–10¹² K. The scintillation was strikingly long-lived at both frequencies over the overall 6–8 years observing period, despite changes of a factor two or more in the mean flux density of many of the sources over the same period. Moreover there was no obvious correlation between the scintillating flux density and the mean flux density, suggesting that the scintillating components were both long-lived and not strongly dependent on the slower intrinsic variability.

Although the Green Bank Interferometer analysis demonstrated that many flat-spectrum sources showed significant scintillation at 8 GHz, it was surprising when strong scintillation was observed at 22 GHz in the Circinus galaxy megamasers [39]. Observations with the Tidbinbilla 70 m telescope of the three strongest lines in the Circinus H₂O megamaser showed rapid, large amplitude variability, with the 564 km s⁻¹ line dropping to one third intensity in less than 10 min. These variations are similar in amplitude and timescale to the variations seen at 4.8 and 8.4 GHz in the three rapid variables [17,21,22], where scintillation has been clearly demonstrated to be the principal cause.

Follow-up VLBI observations of a MASIV sample of both scintillating and non-scintillating sources were undertaken with the VLBA to explore their structure on milliarcsecond scales [40]. These showed that scintillating sources are more core-dominated than non-scintillators. The observations included 0716+71 which showed clear core dominance as well as scatter-broadening between 8.4 GHz and the two lower frequencies, 2.3 and 1.6 GHz [41]. The multi-frequency VLBI observations also revealed angular broadening of similar magnitude in both the scintillating and non-scintillating AGN, yielding a picture in which the scintillation results from localised regions, or “clumps”, distributed

throughout the Galactic disk, but that individually make little contribution to the overall angular broadening [42].

The spectral index dependence of scintillation in the MASIV sources, although highly significant, is not marked, as the sources were originally chosen to have spectral indices of > -0.3 based on non-coeval flux density measurements at 1.4 and 8.4 GHz in order to avoid the “steep-spectrum” tail of the classical steep-spectrum sources [35]. A clearer evaluation of the spectral index dependence is shown in Figure 5 of Rickett et al. (2006) [38], as they sampled a wider selection of the steeper spectral index population.

A more detailed investigation of the spectral index distribution was undertaken as part of the investigation of the redshift dependence based on later coeval measurements at 4.9 and 8.4 GHz [43]. This work highlights its importance as a systematic bias that must be taken into account when exploring possible redshift dependence. Selecting only those sources with spectral indices between -0.4 and $+0.4$, the redshift dependence of ISS was found to be significant, but not significantly steeper than the expected $(1+z)^{0.5}$ scaling of source angular size due to cosmological expansion for a brightness temperature and flux density limited sample. No significant evidence was found for any scatter broadening in the inter-galactic medium, with an upper limit to broadening of $< \sim 110 \mu$ as at 4.9 GHz with 99% confidence [43].

It had long been argued that the apparent simultaneity of the observed variations seen in the radio spectral index of 0716+71 between 5 and 8 GHz, and the observed optical variations were strong grounds that these IDV radio variations were intrinsic to the sources, or at least intrinsic for 0716+71 [15]. However, after undertaking an intensive 4.5 years flux density monitoring campaign at 4.6 GHz, a significant annual cycle in 0716+71 was discovered, thereby clearly establishing the scintillation origin of the IDV in this source [44]. After many years of subsequent searching, such synchronised radio and optical variations were not seen to repeat, and thus were likely random variations. The argument for an intrinsic origin had been earlier weakened as the optical and radio variations over those specific three days were not correlated in detail [45]. The evidence is now overwhelming for interstellar scintillation as the general origin of the cm-wavelength IDV.

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